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RADIOMETEOROGRAPHY AS APPLIED TO UNMANNED BALLOONS[1]

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INTRODUCTION

Widespread surface observations, taken at the same hour, have long been the basis of synoptic meteorology. Modern methods of weather analysis and forecasting require, in addition, synoptic data on the extent, motion, and characteristics of air masses within which and between which the weather takes place. If a complete synoptic picture is desired, vertical soundings up to 4 or 5 kilometers must be made twice daily, or oftener, at stations separated by not more than a few hundred miles; at each station the desired data include the direction and velocity of upper air winds, and the vertical distribution of pressure (p), temperature (t), and relative humidity (f). In some synoptic situations, and in many research problems, it may be desirable to extend observations far above the 5-kilometer level.[2]

For determining these upper air data, three methods of sounding are in wide present use:

(*a*) Free pilot-balloon observed by one or more theodolite stations on the ground; for determining the direction and velocity of upper air winds. Data are evaluated as they are observed.

(*b*) Airplane carrying a recording meteorograph which is returned to the surface station with p, t, and f-data taken during the sounding. Data are evaluated within an hour or two after they are observed.

(*c*) Free sounding-balloon with recording meteorograph, which may be reclaimed after the sounding is made. Data may be evaluated hours or days after they are observed, or may be lost entirely.

These present sounding methods have definite limitations. Complete pilot-balloon observations require clear weather and good visibility. Sounding balloons, while independent of weather, are slow and unreliable. In levels below 5 kilometers airplane sounding, being more rapid and far more certain, is usually preferable to balloon sounding. But the airplane cannot operate safely in unfavorable weather, when soundings are most urgently needed; and above 5 kilometers, which is a practical ceiling for ordinary airplanes, free balloons are necessarily used.

Within recent years the application of radio technique to meteorological balloons has developed new sounding methods which may largely transcend the limitations indicated above. In fair weather or foul, radio transmission can convey instantly to the surface observing station either the balloon's position, or the air characteristics being encountered at any moment during its ascent, or both. In practice either the simple pilot-balloon or the meteorograph-equipped sounding balloon is combined with a small radio transmitter light enough to be conveniently lifted by the balloon. In the case of a radio pilot-balloon, the radio transmitter is excited either intermittently or continuously during the ascent, while bearings are taken on it by one or more directional radio receivers on the ground. In the case of the radio sounding-balloon, the meteorograph continuously indicating p, t, and f as the balloon ascends is caused so to vary some element of the radio transmission, or to interrupt the transmission in such a way, that nearly simultaneous records of p, t, and f during the ascent are conveyed to a receiver on the ground. A radio sounding-balloon can also serve simultaneously as a radio pilot-balloon.

OBJECTS OF PAPER

The objects of this paper are:

(*a*) To review briefly the historical development of radio pilot balloons and radio sounding balloons.

(*b*) To inquire into possibilities of improving the present state of balloon radiometeorography.

(*c*) To evaluate radio balloons in terms of their probable future usefulness.

HISTORICAL[3]

Standard meteorograph.—The standard three-element meteorograph, recording p, t, and f as simultaneous ordinates against time as abcissa, was available in completed form before research on the radiometeorograph began. Its basic elements are shown in figure 1. C is a cylinder revolved at a suitable rate by clockwork; p is the pressure arm, activated through suitable levers by either a syphon vacuum chamber or a Bourdon vacuum tube; t is the temperature arm, activated by a bimetallic strip; f is the relative humidity arm, activated by a multiple strand of human hairs. One or more elements of the standard meteorograph have been included in every radio-sounding balloon.

Radio design.—Balloon radiometeorography became fully practicable when small, efficient, short-wave transmitters were developed in the radio field. Thereafter, radio design by the various investigators in telemeteorography proceeded along similar and conventional lines. The most efficient generator of stable electric oscillations, and hence of receivable radio waves, is a single triode electronic tube connected to suitable external inductance and capacitance, with or without electro-mechanical (crystal) stabilization of frequency.

[1] Presented as a thesis at California Institute of Technology for the degree of Master of Science.
[2] Important military applications of radiometeorography are the determination of ballistic wind and ballistic density for artillery use.
[3] The writer's thanks are due C. F. Talman, Librarian of the U.S. Weather Bureau, for several of the references included.

Figure 2 shows the Hartley self-stabilized oscillator circuit, which has been used by many radiometeorograph investigators. (As will be pointed out later in this paper, better self-stabilized oscillator circuits are available, and should be investigated.) In figure 2, T is the electronic tube, L_1 and L_3 are inductances, C_1, C_2, and C_3 are capacitances; R is a resistance. Frequency and output are

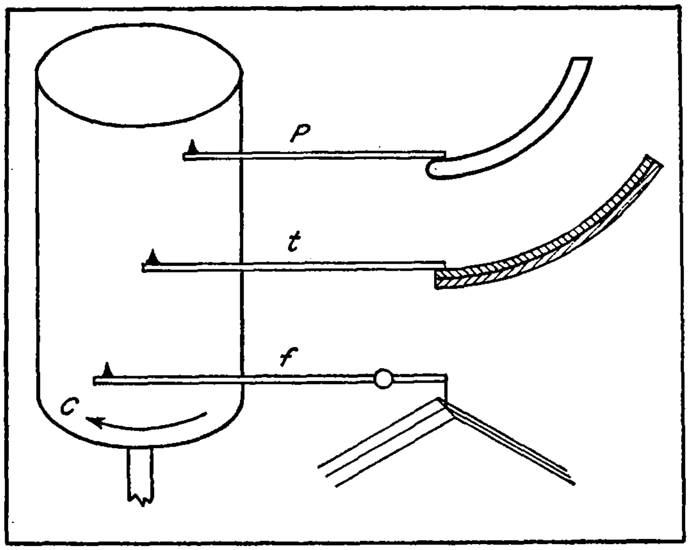

FIGURE 1.—Standard meteorograph principle.

determined by C_1 (usually variable) and L_1. At low-plate voltages the R–C_3 combination may be omitted, the grid being operated at zero bias. All these circuit parts, comprising the actual transmitter, need weigh no more than 100 grams. The battery A, delivering between 0.1 and 0.3 ampere of current at 1 to 4.5 volts, weighs 50 to 200

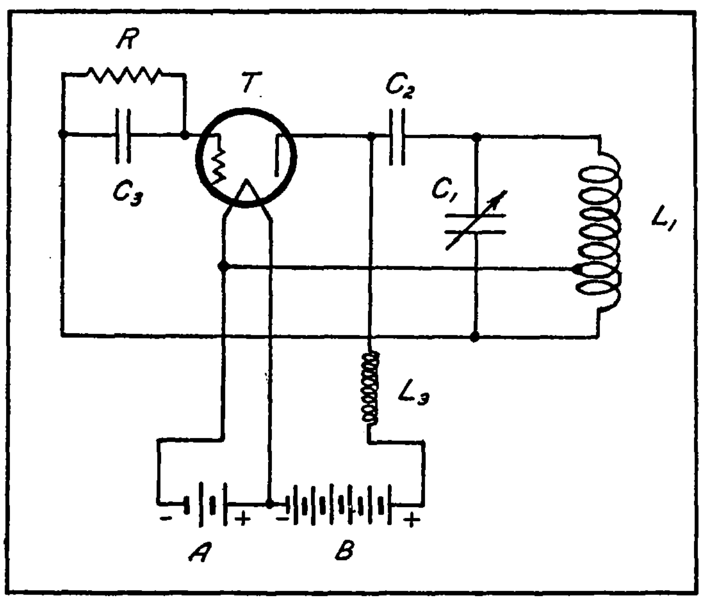

FIGURE 2.—Self-stabilized oscillator circuit.

grams. The battery B, delivering a few milliamperes of current at 25 to 150 volts, weighs 100 to 1,000 grams. It is possible to replace the relatively heavy B battery required for higher plate voltages with a small buzzer-transformer, weighing less than 200 grams and driven by the A battery.

Figure 3 shows a suitable crystal-stabilized oscillator circuit, which has been used by some investigators on account of its superior frequency stability. Here the frequency is determined by the dimensions of the crystal X, and the output is determined by C_1 and L_1. Both L_3 and R may be used, or either alone. Batteries (not shown) are the same as in figure 2.

In order that appreciable amounts of radio-frequency energy may be radiated toward the receiver, the oscillator is suitably coupled to an antenna, which may be a single wire one-half wave-length long, with the entire transmitter suspended at its center. Antenna weight is less than 100 grams. Wave lengths so far used for radio sounding-balloons have ranged from 20 to 150 meters (15,000 to 2,000 kilocycles).

Beginning of telemeteorography.—Outstanding among the pioneers of telemeteorography was Olland (**A**), a Dutch instrument maker. About 1875 he invented a system for the electrical indication of one or more meteorological elements. The same principle is used today in modern radiometeorography (fig. 7). It embodies: (*a*) indicating arms, arranged on a common center, which move radially in response to meteorological changes, one indicating arm serving for each meteorological element; (*b*) fixed reference marks on a circle, between (or in some definite relation to) the indicating arms and their limits

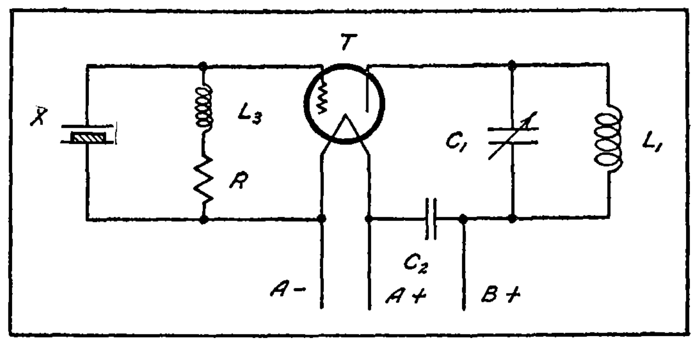

FIGURE 3.—Crystal-stabilized oscillator circuit.

of movement; (*c*) a revolving contact arm, pivoted concentrically with the indicating arms, and making electrical contact with them and with the fixed reference marks in turn during its clockwork-driven progress around the circle.

Contemporaneous with Olland was Van Rysselberghe of Belgium, who developed telemeteorographic apparatus which was widely used.

About 1917 Herath and Robitzsch applied the older methods of telemeteorography to aerology. Their apparatus gave temperature or pressure indication from a kite by means of alternating current in the kite wire.

Radio pilot-balloon.—About 1921 Herath in Germany began experimentation with radio pilot-balloons. The balloon carried a battery-driven buzzer oscillation circuit which was in effect a miniature spark transmitter. This oscillation system has many disadvantages, chief among which is that the radiated energy, being spread over a broad spectrum, gives only a faint signal in the narrow frequency band covered by the receiver. Herath's apparatus was not very satisfactory in either range or accuracy.

About 1923 W. R. Blair (**6**) (Signal Corps, United States Army) began work with radio pilot-balloons. The initial development included a small buzzer transmitter, weighing less than a pound, which could be tracked for 20 minutes to a height of about 3.5 kilometers.

About 1927 Idrac and Bureau (**1**) of France sent up an unmanned balloon equipped with a small continuous-wave (electron tube) transmitter. The total apparatus weight was 2.7 kilograms. Signals on 42 meters were heard during the entire sounding, which extended up into the stratosphere.

About 1928 the Signal Corps, United States Army (**6**) developed an electron-tube transmitter for pilot-balloons, which weighed less than 0.5 kilogram complete with batteries and antenna. The relatively heavy B battery was eliminated in favor of a buzzer-transformer which weighed about 200 grams. Many tests were carried out on wave lengths near 125 meters, including actual tracking of the balloon by means of specially developed direction-finding receivers on the ground, the radio bearings being checked by theodolite observations. The balloon could easily be followed, with useful azimuth readings, to more than 15 kilometers distance from the ground stations. Within 8 kilometers distance, the radio bearings were accurate to ± 0.5 degree.

Radio sounding-balloons.—About 1924 Blair (**6**), in the course of researches mentioned above, did some experimental work with temperature indication from a radio pilot-balloon.

Between the years 1925 and 1933 research in radiometeorography was carried forward chiefly by the investigations of R. Bureau (**3**) in France, P. Duckert (**4**), (**9**), (**11**), in Germany, and P. Moltchanoff (**2**), (**5**), (**7**), in Russia and Germany, who worked contemporaneously on the problem. The first actual soundings were made about 1929.

The principle of Bureau's apparatus is shown in figure 4. *C–I* is a cylinder formed partly of conducting material (*C*) and partly of insulating material (*I*), and rotated by

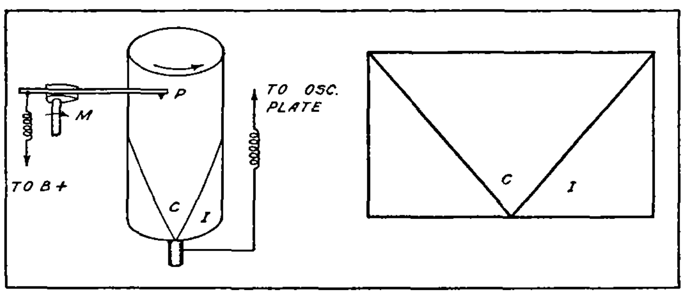

FIGURE 4.—Bureau radiometeorograph principle.

clockwork. *M* is an eccentric cam, rotated at a much faster rate than *C–I*. *A* is an arm indicating temperature, pressure, etc., by the vertical position of its contact point *P*. When *P* is over the conducting portion of the cylinder, dots are transmitted as the cam *M* makes and breaks contact. When the point *P* is over the insulating portion of the cylinder, no dots are transmitted. The number of dots in a series therefore indicates the vertical position of *P*, and hence the temperature, pressure, etc. The system is not limited to the indication of one meteorological element; temperature, pressure, etc., arms can be connected into the circuit in turn by switching cams. For temperature soundings this device gave an accuracy of $\pm 0.7°$ between $+20°$ and $-60°$ C.

Figure 5 shows the principle used by Duckert for continuous indication of temperature. The bimetallic strip *T*, by means of the lever connection *A*, varies the capacity of the condenser *C* in the oscillating circuit, which in turn varies the emitted frequency. A similar principle was used by Blair in the United States.

For pressure indication Duckert used the simple sliding-contactor scheme shown in figure 6. The pressure tube *T*, acting through suitable levers, causes the contact arm *A* to slide along the segment *S*, touching the contacts *c* in turn. Dashes are therefore transmitted, corresponding to definite steps of pressure change perhaps 50 to 100 mb apart.

Duckert used wave lengths between 30 and 60 meters. The accuracy of his apparatus was $\pm 0.2°$ for temperature and ± 1.5 millimeters for pressure. In addition to the more practicable temperature-varied condenser system, he devised a system of continuous-temperature indication based on the fact that an oscillating crystal changes its

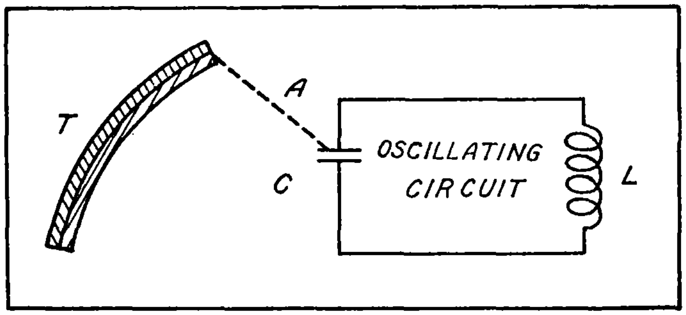

FIGURE 5.—Duckert temperature-indicating principle.

frequency with temperature. In addition, he developed light-weight transmitters and improved methods of thermal insulation, such as enclosing the entire transmitter in a glass vacuum bulb. Duckert's latest radiometeorograph is manufactured commercially by the Telefunken Co. in Germany.

Moltchanoff proposed, in his 1928 paper, a telemeteorographic principle similar to that of Olland. His first working model, however, used for pressure indication the system shown in figure 6; and for temperature indication an extension of this system involving multiple cams which transmitted 1, 2, 3, and 4 dots in turn.

In a later meteorograph, now manufactured commercially by Askaniawerke in Germany, Moltchanoff developed the principle of Olland into the form shown in figure 7. This device keys the transmitter in such a way that the time intervals between dots and dashes, which can be automatically recorded, give indication of pressure, temperature, and relative humidity in turn. In figure 7, *p*, *t*, and *f* are concentrically pivoted and move radially, within the limits of their respective scales, in response to pressure, temperature, and humidity. Separating the *p*, *t*, and *f* scales are the fixed contacts c_1 and c_2 and the synchronizing contact *S*. *p*, *t*, *f*, c_1, c_2, and *S* are all electrically connected to the oscillator plate. Concentrically pivoted with *p*, *t*, and *f*, but insulated from them, is the contact arm *C*, rotated by clockwork at about two revolutions per minute and electrically connected to *B*+. In the course of *C*'s revolution, the platinum wire *W* contacts *p*, c_2, *f*, *S*, *t*, and c_1 in turn, transmitting a dot for each contact except *S*, which results in a dash. The time interval between a fixed contact such as c_1 and a movable contact such as *p* indicates the pressure, etc., being encountered by the device at the time. The entire radiometeorograph, which operates on wave lengths between 25 and 100 meters, weighs 1.4 kilograms. Reception and evaluation are best accomplished by a standard facsimile receiver, whose recording cylinder is synchronized with the contact arm *C*. Curves having time (altitude) as abcissa and p, t, and f as ordinates are thus directly recorded as the sounding is made.

About 1932 Väisälä (**12**), in the course of radiometeorograph research, devised some notably light batteries of lead-acid type. His 4-volt, 15-ampere-minute A battery weighed 38 grams; and his 72-volt, 1-ampere-minute B battery weighed 72 grams.

For additional details of radiometeorograph development, the reader is referred to the historical paper by Duckert (**8**).

POSSIBILITIES OF IMPROVEMENT IN RADIOMETEOROGRAPHY

Direction of future development.—Present models of the radiometeorograph give satisfactory performance. Future development will probably be directed chiefly toward lightness, simplicity and low cost. For radiometeorographs operating up to 6 kilometers altitude, the following weights are desirable upper limits: Batteries and other power supply, 150 grams; transmitter (including thermal insulation and antenna), 100 grams; meteorograph and clockwork, 150 grams; balloon, 150 grams; total weight, 550 grams. For radiometeorographs operating up to 30 kilometers: Batteries, etc., 250 grams; transmitter, etc., 150 grams; meteorograph, etc., 150 grams; balloon, 250 grams; total weight 800 grams. Simplicity is to be gained by standardizing the best and simplest telemeteorograph system available, and by using the simplest radio transmitter circuit that will give adequate performance (output and frequency stability). Low cost can be obtained partly through this simplification, and partly through manufacture of standardized units in fairly large quantities. A desirable upper limit of cost is $25 (exceeded at present) which would enable the radiometeorograph to compete economically with the sounding airplane, even assuming the loss of the balloon.

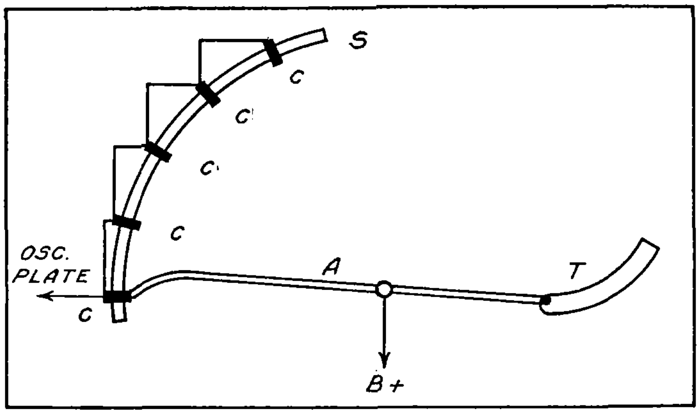

FIGURE 6.—Duckert-Moltchanoff pressure-indicating principle.

Possible methods of p, t, etc. indication.—The possible ways in which meteorological changes can be translated into intelligible radio indications are four in number, as follows:

(*a*) By varying the intensity of the transmitted signal. Unsatisfactory, as the signal intensity at the receiver is also subject to undesired and uncontrolled variation.

(*b*) By varying carrier frequency (bimetallic strip forming or mechanically coupled to one plate of a condenser in the oscillating circuit, etc.). This system is used and advocated by Duckert, who stresses the advantage of continuous temperature indication. At fairly uniform rates of ascent, however, a smooth temperature curve can easily be plotted from points intermittently recorded. Moreover, where the carrier frequency itself indicates the meteorological element, inordinate precautions are necessary to avoid slight undesired frequency changes that would otherwise be negligible.

(*c*) By modulating the carrier frequency and varying the modulation frequency. Believed to be too uncertain, and too cumbersome from the viewpoint of weight and cost.

(*d*) By interrupting, or keying, a signal of reasonably constant amplitude and frequency, which may be either continuous wave- or tone-modulated. This system, as exemplified in the Bureau and Moltchanoff devices, is believed by the present writer, in view of the known characteristics of radio apparatus and radio transmission, to be most worthy of future development.

Improvement of indicating meteorographs.—In the opinion of the present writer, the telemeteorograph as invented in 1875 by Olland and adapted to radio sounding-balloons more recently by Moltchanoff, has not been surpassed in simplicity and completeness of working principle by any later development. It is light, relatively simple, and permits the direct recording of practically continuous p, t, and f curves against time or altitude. It is possible that some better telemeteorographic principle will be invented. But as the Olland principle is now amply satisfactory, it would appear more profitable to concentrate immediate research in radiometeorography on other subfields such as radio technic.

Radio improvements, general.—In this field much progress in the direction of lightness, simplicity, and low cost remains to be made. Conventional radio apparatus, as so far applied to radiometeorography, can be considerably improved. It appears to the present writer that the most favorable short waves (5 to 20 meters) have not been used. Moreover, the field of ultra-short waves (1 to 5 meters) and micro-waves (<1 meter) has not even been touched.

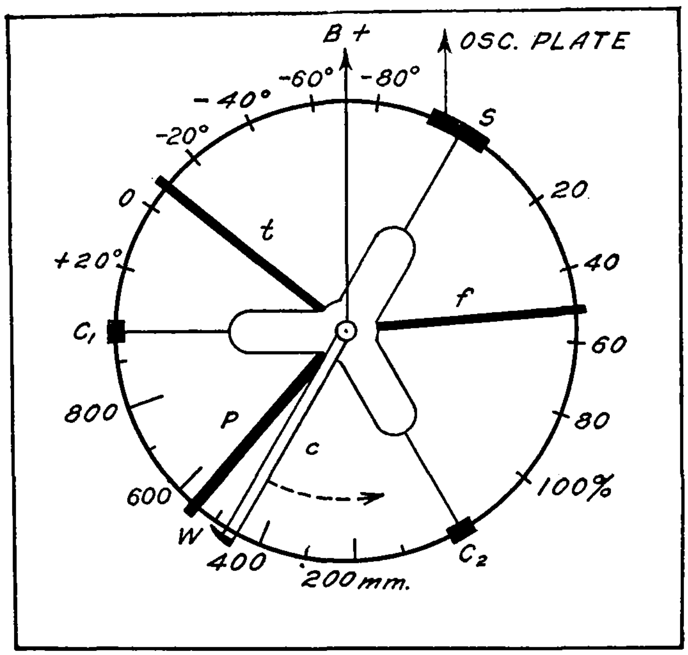

FIGURE 7.—Olland telemeteorograph principle.

Power supply improvements.—Small lead-acid batteries of A and B types, as developed by Väisälä, are probably near the ultimate in light-weight design. Dry-cell batteries are more convenient to use, and would probably give satisfactory electrical capacity in relation to weight. Dry cells which have been stored for any length of time, however, are in uncertain condition, whereas lead-acid batteries can be filled and charged before use. Also, the constant-voltage characteristic of the lead-acid A battery is particularly suitable for electronic filament operation. As a substitute for the B battery, the buzzer-transformer is worthy of careful consideration, particularly as it produces a relatively broad, tone-modulated signal which is easily received. Its performance, however, depends on the adjustment of its vibrating contact, which may change considerably in response to large temperature changes. Enclosure of the contact or the entire device in a glass vacuum bulb, which might also enclose the entire transmitter, would be worth considering.

Improvements in ordinary short-wave technique. ($\lambda > 5$ meters).—In contrast to the 20 to 150 meters spectrum so far used in radiometeorography, wave lengths below 15 meters have three advantages: (*a*) Effective transmitting antennas are smaller and lighter; (*b*) oscillator circuit arrangements are smaller, lighter, and often simpler; (*c*) the 5 to 15 meters region is removed from the high-power interference which blankets the long-range wave lengths above 15 meters.

Receivers.—Receivers for 5 to 15 meters are of conventional design, somewhat refined, and can easily be combined with recording devices. Moreover, it is possible to use loop aerials for tracking radio pilot-balloons at wave lengths down to 5 meters. Whether these shorter waves would suffer greater directional vagaries than longer waves, would have to be determined by experiment.

Transmitters.—Before optimum transmitter design in radiometeorography is reached, one important question must be answered: Is crystal frequency stabilization necessary, or desirable? The crystal does insure better frequency stability. But it also entails slightly greater weight and complexity, and considerably greater cost. Using tone-modulated waves, as produced by buzzer-transformer plate supply, self-stabilized circuits will certainly suffice, and with correct circuit design and adequate thermal insulation, they may suffice for continuous waves. The tuned plate-tuned grid circuit, or the simpler tuned-plate variation of it shown in figure 8, is inherently more stable than the ordinary Hartley circuits so far used in radiometeorography. With suitable thermal insulation, it might give frequency stability adequate for all practical purposes. In addition, simple and cheap methods of frequency stabilization, such as the resistance-stabilized oscillator of Kusunose and Ishikawa (**13**), are available.

Antennas.—So far most investigators have used a half-wave dipole antenna, the upper end being tied to the balloon, the transmitter being connected in the middle (current feed), and the lower end hanging free. A more stable arrangement, from the viewpoint of swinging, etc., in shifting air currents, might be hanging the transmitter (perhaps equipped with damping vanes of light pasteboard) at the lower end of the half-wave dipole, which in this case would be voltage-fed.

Use of ultra-short waves and micro-waves. ($\lambda < 5$ meters).—This entire field, entirely unexplored so far as meteorography is concerned, shows considerable promise in certain directions. According to Beverage, Peterson, and Hansell (**14**) wave propagation in this region is in general optical with considerable diffraction at the higher wave lengths, becoming strictly optical at about λ 1 meter. In balloon radiometeorography this optical characteristic is no disadvantage, as there will always be a direct air path between a normally rising balloon and a properly located ground station.

Receivers.—Receivers for this wave-length region are highly specialized, being mostly of superregenerative and superheterodyne types. They can easily be adapted to radiometeorographic indication and recording. For radio tracking of pilot-balloons, several possibilities appear. The half-wave dipole, giving a minimum signal when the transmitter is on a line with it, is compact and easily movable at wave lengths below 10 meters. Antenna array or "beam" systems, as developed by Yagi (**15**) and others, become reasonably small and wieldy at about λ1 to 2 meters, and have distinct direction-finding possibilities. Finally, in the micro-wave region below λ0.2 meter, solid reflectors (and even lenses) of optical type are feasible, offering some interesting possibilities in three-dimensional direction finding.

Transmitters.—In the ultra-short wave and micro-wave regions several types of transmitters, as summarized elsewhere by the present writer (**16**), are available, though probably not all suited to radiometeorography. The magnetron oscillator, which reaches very short wave lengths, is definitely too heavy. The Barkhausen-Kurz oscillator circuit, also capable of producing micro-waves, requires relatively high grid and plate voltages; whether the requisite power supply could be made light enough is questionable. Regenerative oscillators, which operate at low plate voltage, are limited to wave lengths above 2 meters when ordinary electronic tubes are used.

Very small electronic tubes have recently been developed by Thompson and Rose (**17**). These tubes enable

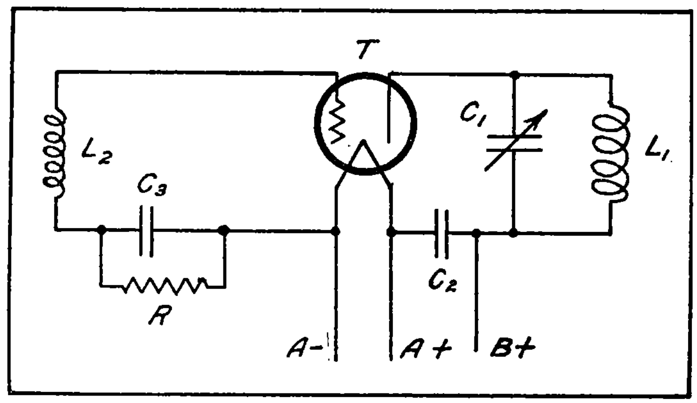

FIGURE 8.—Tuned-plate oscillator circuit.

the regenerative oscillator to reach wave lengths less than 1 meter and may permit other circuit developments of importance in radiometeorography.

PROBABLE FUTURE USEFULNESS OF RADIO BALLOONS

Classification of types.—Radio balloons will naturally be grouped into two types, pilot-balloons and sounding-balloons, as they are used (*a*) to determine upper-air motion or (*b*) to determine upper-air characteristics. In addition, the writer envisions pilot-balloons and sounding-balloons of two general classes: (1) low-altitude (up to 6 kilometers) and (2) high altitude (up to 30 kilometers). These two classes may be exactly similar in principle, but must differ in certain details such as power of radio equipment, thermal insulation, scale of meteorographic instruments, etc.

Radio pilot-balloons.—Any radio sounding-balloon can, of course, serve simultaneously as an ordinary pilot-balloon in clear weather; or as a radio pilot-balloon in poor visibility, provided that adequate direction-finding receivers are available on the ground. It is possible that, due to wave-transmission characteristics, radio pilot-balloons will develop along separate lines, using a frequency spectrum widely different from that suited to radio sounding. It is also possible, however, that the same frequency range may serve for both sounding and tracking; in which case one might envision a combined radiometeorographic instrument of either low-altitude or high-altitude type, which could be used complete for sounding with or without tracking, or used for tracking only without its detachable meteorographic unit. In any case, it is clear that for upper-wind determination in poor visibility the radio pilot-balloon has no practical competitors, and its use is clearly indicated under these conditions.

Radio sounding-balloons.—Subdivided into probable low-altitude and high-altitude classes.

Low-altitude class (up to 6 kilometers).—This class competes with airplane sounding, which is already satisfactory, getting the data back with certainty for evaluation 1 or 2 hours after they are taken. In weather dangerous to flying, which is often the form of weather most deserving of investigation by soundings, the radio balloon is markedly superior to the airplane, and its use is indicated even at present cost levels. Even in fair weather, the radio balloon gets the data back more quickly than the airplane, and may, with standardization and mass production, prove superior from a cost viewpoint, particularly in settled regions where the percentage of returned balloons is reasonably high.

High-altitude class (up to 30 kilometers).—This class competes with the ordinary sounding balloon, and should practically supplant the latter in most investigations. The radio development is incomparably quicker, the data being evaluated as they are taken rather than days or weeks later. Moreover, the radio balloon is far more certain, particularly in sparsely settled regions where the balloon may never be recovered. The balloon radio installation need add but very little to the total high-altitude sounding-balloon cost, and the ground radio installation should be more than justified by vastly superior results, particularly where many soundings are made from a single fixed or mobile station.

Need for standardization.—All radiometeorographic possibilities should be explored, as rapidly as possible, in order to determine: (*a*) optimum frequency (wave length) ranges for various types of radiometeorographs; (*b*) optimum apparatus design for most efficient use of these frequencies. Considering past and present trends in the development of both meteorographic and radio technique, it seems probable that such optimum design, once reached in the present state of the art, will remain reasonably efficient for some years. This will permit the standardization and large-scale production which alone can make the full benefits of radiometeorography available to modern meteorology.

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